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Satellite Reliability Model Supporting End-of-life Operations Success

Anton ROIG, Christophe ETCHEVERRY, Karine ETIENNE
Centre National d'Etudes Spatiales (CNES)
18 Avenue Edouard Belin, 31400 Toulouse, France
+33 6 63 73 98 71
anton.roig@cnes.fr

ABSTRACT

The increasing number of satellites in orbit and the upcoming deployment of constellations of hundreds of small satellites raises the problem of orbital debris and saturation of main LEO and GEO orbits. Currently, about sixty percent of satellites are deorbited at their end of life, including thirty percent deliberately with a propulsion system. The increase in the number of debris has led to the implementation of preventive and corrective actions at an international level to ensure the availability and safety of these orbits for future space projects. It therefore appears necessary to guarantee with the best estimate possible the operations of passivation and withdrawal of service for satellites in orbit at their end of life.

This paper presents and illustrates – with the case of the French National Space Agency's scientific satellite TARANIS based on the Myriade microsatellite generic platform – different approaches to improve satellite reliability model. They are based on Bayesian and Chi-Square techniques that rely on operations feedback in order to provide a more realistic risk assessment, closer to the value statistically observed in orbit.

This will lead to a better compliance to space debris national and international standards – as the French Law on Space Operations or the ISO Space Systems - Space Debris Mitigation Requirements – concerning end-of-life operations. That way, it will guarantee a safe access and operations in space for future missions by limiting the proliferation of space debris in already crowded Earth orbits.

Acronyms:
AOCS = Attitude and Orbit Control System
CAD = Computer-Aided Design
CTA = Active Thermal Control
EEE = Electrical, Electronic and Electromechanical
FIT = Failure In Time
FR = Failure Rate
GS = Solar Generator
LEO = Low Earth Orbit
LOS = French Law on Space Operations
MAG = Magnetometer
MEGS = Solar Generator drive Mechanism
MTB = Magneto Torquer Bar
MTTF = Mean Time To Failure
OBC = On Board Computer
PCDU = Power Conditioning and Distribution Unit
P/F = Platform
RW = Reaction Wheel
SST = Standard Star Tracker
REX = Experience feedback
RX = Receiver
R&T = Research and Technology
SAS = Sun Analog Sensor
SPOF = Single Point Of Failure
TX = Transmitter

Key words – Satellite, Reliability, Space debris

I. INTRODUCTION

In the last few years, with the constantly increasing number of space debris – especially in LEO – and after recent in orbit collisions between active and defunct satellites, several international organizations of big space nations have established standards to encourage global efforts to deal with this issue. They require, among others:

- To avoid the release of Mission Related Objects into Earth orbit during the operations;
- To avoid break-ups in Earth orbits during operations and after the end of the mission by passivating all the sources of energy stored on board;
- To remove spacecraft and launch vehicles orbital stages from the LEO through a controlled re-entry or an uncontrolled one within 25 years, and GEO protected regions through maneuvers to a higher orbit of about 200km;
- To perform the necessary actions to minimize the risk of collision with other space objects.

In this context, the probability of successful service withdrawal is a major requirement.
It directly determines the long-term evolution of the debris population in flight: all the simulations carried out by the agencies as part of the IADC (Inter-Agency

Space Debris Coordination Committee) studies were carried out with a success rate set at 90% (percentage of satellite withdraw versus population of end-of-life satellites).
It also determines the criteria for deorbitation at the end of the mission with regard to the events (anomalies, breakdowns, etc.) experienced by the satellite.

II. SATELLITE END-OF-LIFE OPERATIONS

1. Withdrawal from Service

The value currently set by the 2017 Technical Regulations for probability of success of carrying out the withdrawal operations is 0.85.
Internationally, in ISO 24113:2019, the absolute probability of successful withdrawal is 0.90.

The probability of 0.85 does not include the availability of consumable energy resources which is the subject of another clause.
The service withdrawal manoeuvers include the following steps:

1. Satellite deorbitation/re-orbitation to free the LEO and GEO most used orbits:
   - If the implementation is done in protected geosynchronous (GEO) regions: the satellite withdrawal operations must be such that it cannot return to the protected area naturally within 100 years.
   - If the implementation is in the protected Low Earth Orbit (LEO): the satellite withdrawal operations must be such that it must no longer be present in LEO orbit within 25 years after the end of the mission. The satellites are designed to carry out an atmospheric reentry within 25 years after their end of operational life.

2. The fluid passivation of the satellite: It corresponds to the emptying of the propellants and to the depressurization of all the pressurized systems present in the satellite, such as the chemical propulsion systems and plasma too. At the end of the fluid passivation, the resulting pressure must not exceed a few bars (in concordance with the technical regulations).

3. The electric passivation of the satellite: It corresponds to the definitive de-energization of all systems and equipment of the satellite which could either present risk for the integrity of the satellite or disturb other orbital objects. This includes:
   - The shutdown and isolation of all actuators (AOCS) such as reaction wheels or gyroscopic actuators.
   - The shutdown of all equipment capable of transmitting (RF).
   - Disconnection and isolation of the battery and of all other sources of electricity generation (solar generator for example).

In summary, the probability of successful withdrawal of service is considered to be the reliability of the satellite resources necessary for withdrawal of service under the conditions specified previously.

This study is generally done in interface with the system engineers and electrical and propulsion architects of the project in order to identify the minimum architecture necessary to carry out the end of life operations of the satellite.
The main difficulty of the study is to have access to the failure rates of the equipment necessary for these operations. Therefore, it is needed to anticipate the end-of-life probability success calculation from the preliminary design stages, by choosing components and equipment for which the suppliers have carried out reliability studies, tests or have already flown long enough. As a last resort, it is also possible to make relevant and justified analogies - based on expert judgment - with equipment from satellites that have already flown.

2. Evaluation of the Satellite Reliability

This part presents the methodology to evaluate the satellite reliability – needed to calculate the probability of successful end-of-life operations – with the highest precision possible thanks to various mathematical models.

a. Theoretical Reliability

The theoretical reliability assessment of a satellite is based on the following hypotheses:

- During the mission, the components are assumed to have constant failure rates (λ), and to be able to fail independently of each other.
- The exponential law is used to calculate the reliability (R) according to the formulas 1, 2 and 3:
  - For a single point of failure:

$$R_{SPOF} = e^{-\lambda_{ON}*t} \tag{1}$$

  - For active redundancy:

$$R_{Active}(m/n) = \sum_{i=0}^{n-m} C_n^i (1 - e^{-\lambda_{ON}*t})^i * (e^{-\lambda_{ON}*t})^{n-i}$$
$$with\ C_i^n = \frac{n!}{i!(n-i)!} \tag{2}$$

  - For passive redundancy:

$$R_{Passive}(m/n) = e^{-m*\lambda_{ON}*t}\left[1 + \sum_{i=0}^{n-m} \frac{(1 - e^{-\lambda_{OFF}*t})^i}{i!} \prod_{j=0}^{i-1}(j + m\frac{\lambda_{ON}}{\lambda_{OFF}})\right] \tag{3}$$

- The failure rate of elements that are not in operation (λ_{OFF}) is assumed to be 1/10 of the failure rate (λ_{ON}) for EEE components.
- For equipment with a duty cycle (α) other than 100%, an equivalent failure rate is calculated using the formula 4:

$$\lambda_{equipment} = \alpha * \lambda_{ON} + (1 - \alpha) * \lambda_{OFF} \qquad (4)$$

However, the results of this method are always very pessimistic regarding with the real performances of the satellites. Indeed, the main source of uncertainty of the method comes from the MIL-HDBK-217 standard which is the most widely used empirical reliability prediction model for electronic equipment.
This military handbook was developed in 1961 with the purpose of establishing and maintaining consistent and uniform methods to estimate the inherent reliability of military electronic equipment and systems.
However, it is not updated since 1995, and incomplete since new components, technologies and quality improvements are not covered. As a result, actual in-orbit performance has often showed largely conservative results leading to potential overdesign, reduced performance and cost effectiveness of satellite design.
Some R&T had been conducted by the French agency and Space industrials – Airbus Defence and Space and Thales Alenia Space – in order to update and revitalize the MIL-HDBK-217 standard in recent years and a Reliability models extensions User Guide has been published. However, the handbook remains quite pessimistic even with this update.

b. REX and Bayesian Techniques

A forecast estimate of equipment reliability can be consolidated by taking into account the effective operating life of identical equipment, operating since its launch in similar environments and conditions of use (including temperature), by application of Bayesian techniques – as illustrated on Figure 1 :

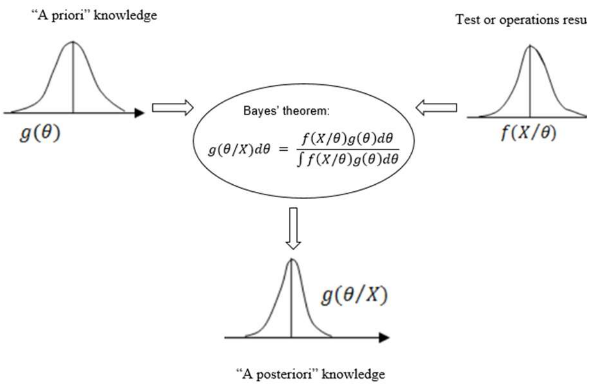

Figure 1: Principle of Bayesian inference

The reliability is characterized by a Poisson distribution, i.e. the probability of obtaining k failures during a cumulative time T is proportional to:

$$f(k \,/\, \lambda,\ T) = \frac{(\lambda T)^k}{k!}\, e^{-\lambda} \qquad (5)$$

with λ the failure rate (the unknown parameter to estimate).
In our case, we have "a priori" information: the theoretical reliability estimate. These assessments are considered to be performed at 60% confidence. By considering this theoretical failure rate no longer as a simple value but as a random variable, it is possible to consider a law "a priori".

For a Poisson distribution, it is possible to consider a law "a priori" Gamma, which is the conjugate of the Poisson law:

$$g(\lambda \,/\, k,T) \ = \frac{\lambda^k T^{k+1} e^{-\lambda T}}{k!} \qquad (6)$$

The formula 6 can also be expressed by formula 7, i.e. a Gamma law with parameters $\alpha = k + 1$ and $\beta = T$, because Γ(k+1) = k!:

$$g(\lambda \,/\, \alpha,\beta) \ = \frac{\lambda^{\alpha-1}\beta^{\alpha}e^{-\beta\lambda}}{\Gamma(\alpha)} \qquad (7)$$

The scale parameter β is then equal to α/λ because $E(\lambda) = \alpha/\beta$ and the shape parameter α can be calculated by solving the equation of formula 8 for a level of confidence of n%:

$$F^{-1}Gamma(n\%, \alpha, \beta) = \alpha/\beta \qquad (8)$$

α = 1.765156924 for a 60% confidence level of the estimation.

The a priori law can be enriched by REX data (k failures during a cumulative period T) and lead to the "a posteriori" distribution of formula 9.

$$g(\lambda/\alpha,\beta,k,T) = \frac{\lambda^{\alpha+k-1}\beta^{\alpha+k}e^{-(\beta+T)\lambda}}{\Gamma(\alpha+k)} \ = \Gamma(\beta+T,\alpha+k) \qquad (9)$$

The point estimator of the $\lambda_{bayesian}$ failure rate is the average value of the Gamma distribution "a posteriori".

$$\boxed{\lambda_{bayesian} = \frac{\alpha+k}{\beta+T}} \qquad (10)$$

where k = number of failures; T = total operating time in hours.

In this way the Formula 10 permits to combine a theoretical reliability with operation results of similar equipment in order to consolidate the satellite reliability – as shown for the case of TARANIS in Chapter III.

c. REX and Chi-Square Method

Another classic approach to compute the failure rates of one unit from the REX, test or in orbit data, is the Chi-Square distribution. When assuming that the life of the device follows an exponential law with constant failure rate (λ) and that failures are independent, the statistic "twice the total test time T divided by the mean life (θ = 1/λ)" is distributed as a Chi-Square χ^2 (α, n) where α is the confidence level and n the degree of freedom:

$$MTTF > \frac{2*T}{\chi^2_{1-\alpha}(2*k+2)} \qquad (11)$$

where T = Total operating time in hours; $1-\alpha$ = Confidence and k = Number of failures.

And so the estimator of the failure rate is defined by the formula 12:

$$\boxed{\lambda_{Chi-Square} = \frac{\chi^2_{1-\alpha}(2*k+2)}{2*T}} \qquad (12)$$

This model is useful when a lot of equipment's operating data is available – for satellite constellations using the same platform for example. When the total operating time is small, the estimation is very pessimistic and not reflecting the reality. This method will also be illustrated in the next chapter with the satellite TARANIS, using a generic microsatellite platform Myriade.

III. TARANIS END-OF-LIFE OPERATIONS

1. Satellite Presentation

TARANIS (Tool for the Analysis of RAdiation from lightNIng and Sprites) is an observation microsatellite of the French Space Agency CNES which will study the transient luminous events that form over the clouds during thunderstorms around the globe.
The TARANIS mission is dedicated to study the magnetosphere-ionosphere-atmosphere coupling via transient processes.
The TARANIS satellite will observe all the emissions above thunderstorm and will allow to simultaneously measure:
- Transient Luminous Events (TLEs)
- Terrestrial Gamma-ray Flashes (TGFs)
- Electric and Magnetic emissions,
- Runaways electrons beams.

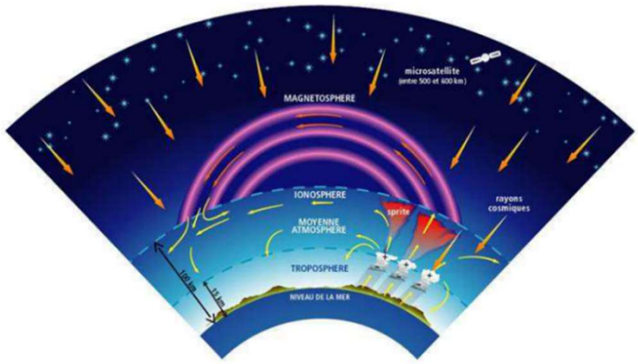

Figure 2: Transient luminous events observed by TARANIS

The satellite will be launched this year (end of 2020) on a sun-synchronous orbit at an altitude of 700 kilometers.

The reliability of the functions necessary for TARANIS end of life operations must be better than 0.85 at the end of the mission duration.
This TARANIS mission duration in orbit is 62 months (5 years and 2 months) counted as follows:

- Satellite Launch and Early Orbit Phase and fine positioning: 0.5 month;
- In-flight commissioning: 2.5 months;
- Routine phase: 45.0 months;
- Mission extension: 12.0 months;
- Disposal phase: 2.0 months.

2. Satellite Architecture

The TARANIS satellite is associating a Myriade microsatellite platform and a payload including the scientific instruments.

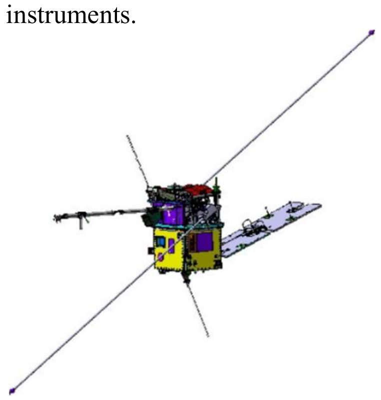

Figure 3: TARANIS CAD model

a. Scientific Payload

The TARANIS scientific payload is constituted by the instruments:
- MCP, a set of 2 cameras and 3 photometers measuring the luminance in several spectral bands at high resolution;

- XGRE, a set of 3 detectors to measure high energy photons (20 keV to 10 MeV) and relativistic electrons (1 MeV to 10 MeV);
- IDEE, a set of 2 electron detectors to measure their spectrum between 70 keV to 4 MeV together with their pitch angle;
- IME-BF, a low frequency antenna to measure the electric field to a frequency up to 3.3 MHz;
- IME-HF, a high frequency antenna to measure the electric field at frequencies of 100 kHz to 30 MHz;
- IMM, a tri-axis magnetometer to measure the magnetic field.

b. Myriade Platform

The TARANIS platform is based on the Myriade Microsatellites Series recurrent product line, using a new "200kg" structure. It includes the support functions for in flight operations as provision of electrical power, command and data handling, telecommunications, thermal control and propulsion for orbit maneuvers:

- Propulsion system
- GS panels
- MEGS
- Battery
- On Board Computer
- Magnetometer
- Sun Analog Sensors
- Reaction Wheels
- Stellar Sensor
- Gyrometers
- S-band transmitters (in passive redundancy ½)
- S-band receivers (in active redundancy ½)
- S-band antenna
- X-band transmitter and antenna
- Active Thermal Control

3. Presentation of the Problematic

At the end of the TARANIS mission, the satellite will be deorbited and then passived.
In this case the desorbitation consists in lowering the orbit altitude of the satellite, allowing it to enter the atmosphere in less than 25 years.
In order to be able to perform these desorbiting maneuvers:
- The Payload and interface circuits on the Platform side are not necessary;
- The resources allocated to the Payload will allow us to consider additional redundancies for the Solar Generator;
- All other satellite functions and equipment are required.

The fluid passivation is ensured by a procedure allowing the emptying of the propellant which does not differ from the nominal procedures.

The electrical passivation is ensured by a discharge of the battery, an orientation of the GS back to the sun and an opening of the GS sections.

The probability of success of the satellite end-of-life operations is the reliability of the system previously identified composed by all the required equipment to perform these operations.

4. Theoretical Reliability of the Satellite

For platform equipment the development was largely based on equipment purchased "off the shelf", for which the directives given to equipment manufacturers were to deliver for information – when it existed – the reliability documentation available from previous programs.

Thus, the failure rates of the equipment considered in Table 1 come either from supplier data or from analogy with other programs.

Table 1: Reliability estimation of the TARANIS platform

System	Equipment	Failure rate [FIT]	Use rate	Quantity
Avionics	OBC	1550	100%	1
Power	GS	100	100%	1
	PCDU	1175	100%	1
	Battery	110	100%	1
	MEGS	830	100%	1
TTC chain	Rx	1160	100%	2
	Tx	830	10%	2
	Antennas	204	100%	2
	Diplexer	10	100%	1
Thermal	CTA	300	100%	1
SCAO	RW (X, Y1 et Z)	1304	100%	3
	RW (Y2)	1304	10%	1
	MAG	412	100%	1
	MTB	7	100%	3
	SAS	15	100%	3
	SST	500	100%	1
	Gyrometer	5815	1%	1
	Propulsion	1524	10%	1

With these data and using Formulas 1, 2 and 3, the following results are obtained concerning the theoretical reliability of the TARANIS platform (without and with the one-year mission extension):

P/F Reliability (for LOS)	
@ 4 years and 2 months	@ 5 years et 2 months
0.68	0.62

These numbers are very pessimistic in comparison with the results of previous missions based on a Myriade Platform and are not enough to respect the specification of 0.85 previously defined.

5. *Bayesian Reliability*

The Bayesian method previously defined is used to consolidate the theoretical failure rates.

These techniques allow the theoretical values of failure rates to be combined with the REX Myriade.
Thus, the "a priori" failure rate, considered with a level of confidence of 60%, constitutes the "a priori" knowledge.
The Myriade REX indicates that the cumulative time in operating orbit of the Myriade platforms reaches 31 years and 4 months (i.e. T = 469,440 hours of operation) without failure (k = 0). For equipment in several copies, the overall operating time is multiplied by their number (taking into account the rate of use). Some equipment such as MEGS and SST not being present on Myriade "minimal" type platforms, the operating time is only 269,000 hours. For Myriade Wheels, we find in the REX that the cumulative operating time reaches 145 years and 4 months (T = 1,273,080 h).

Thus, using Formula 6, this recalibration makes it possible to obtain much better posterior failure rates:

Table 2: Adjusted reliability data for the TARANIS platform

System	Equipment	Failure rate [FIT]	Cumulative operation time	New Failure Rate [FIT]
Avionic	OBC	1550	469 440	1100
Power	GS	100	469 440	98
	PCDU	1175	469 440	895
	Battery	110	469 440	107
	MEGS	830	269 000	737
TTC chain	Rx	1160	938 880	887
	Tx	830	93 888	812
	Antennas	204	938 880	184
	Diplexer	10	469 440	10
Thermal	CTA	300	469 440	278
SCAO	RW (X, Y1 et Z)	1304	1 273 080	672
	RW (Y2)	1304	1 273 080	672
	MAG	412	469 440	371
	MTB	7	1 408 320	7
	SAS	15	1 408 320	15
	SST	500	269 000	465
	Gyrometer	5815	4694	5727
	Propulsion	1524	46 944	1465

With the new failure rate values recalculated using Bayesian techniques, the following values are obtained for the Platform reliability using Formulas 1, 2 and 3:

P/F Reliability (for LOS)	
@ 4 years and 2 months	@ 5 years et 2 months
0.76	0.71

The estimation is less pessimist but still not enough to respect the specification.

In order to improve it, it is possible to group all the equipment in series to have a less pessimistic estimate of the reliability:

Table 3: Adjusted and grouped reliability data for the TARANIS platform

Equipment	Failure rate [FIT]	Use rate	Quantity	Cumulative operation time	New Failure Rate [FIT]
Grouping of equipment in series	9305	100%	1	269 000	3848
Battery	110	100%	1	469 440	107
String GS	100	100%	1	469 440	98
Rx	1160	100%	2	938 880	887
Tx	830	2%	2	93 888	812

where (FR is the Failure Rate in FITS):

$$FR_{\text{Grouping of equipment in series}} = FR_{OBC} + FR_{PCDU} + FR_{MEGS} + FR_{ANTENNAS} + FR_{DIPLEXER} + FR_{CTA} + FR_{RW} + FR_{MAG} + FR_{MTB} + FR_{SAS} + FR_{SST} + FR_{GYRO} + FR_{PROPU} = 9305\ FITS$$

In this case the new results are better:

P/F Reliability (for LOS)	
@ 4 years and 2 months	@ 5 years et 2 months
0.87	0.84

The specification (0.85) is respected for a 4 years and 2 months' nominal mission, without mission extension. This method is not enough to demonstrate the 0.85 probability with a mission extension of one year.

6. *Chi-Square Reliability*

For a platform with so much REX as Myriade, the most efficient way method is the Chi-Square technique, that uses only REX and no theoretical values.
By application of the Formula 12 with T = 269 000 h and a confidence level of 60%, it is possible to obtain the $\lambda_{Chi-Square}$. The evolution of TARANIS platform reliability (an exponential law with parameter $\lambda_{Chi-Square}$) in time is given in Figure 4:

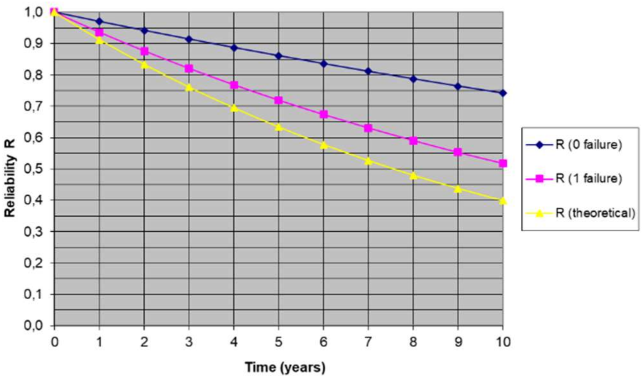

Figure 4: Evolution of TARANIS platform reliability in time

For information, the curve of theoretical reliability obtained in Chapter IV. 4. and the curve obtained with Chi-Square method with one failure are also drawn. The curve with one failure would correspond to the pessimistic hypothesis that a failure appears immediately after the last observation.

With this technique, the reliability is the less pessimistic:

P/F Reliability (for LOS)	
@ 4 years and 2 months	@ 5 years et 2 months
0.88	0.86

The Chi-Square technique allowed to demonstrate the needed probability of successful TARANIS' end-of-life operations – even with the one-year mission extension – that was needed to obtain the authorization for the launch of the satellite.

IV. CONCLUSION

A successful End-of-life disposal and the compliance to Space Debris laws and requirements are issue of interest and importance for space agencies such as the CNES.
The different approaches presented in the publication to overpass uncertainties of the current reliability models using experience feedback are expected to lead to more realistic figures and therefore to better decisions for the need of a disposal or a possible life extension for example.
Being able to dispose a satellite in a safe and reliable manner has a fundamental importance in order to limit the exponential proliferation of space debris in already crowded orbits.

REFERENCES

1. A. Roig, "Estimate of the reliability of the Myriade platform", CNES 2019
2. A. Roig, "Assessment of the probability of success of TARANIS end-of-life operations", CNES 2019
3. A. Cabarbaye, "From quantifying risk to optimizing systems", Cab Innovation 2017
4. J.-F. Gajewski, "Modeling of the degradation of satellite equipment from on-board and ground observables", Airbus/CNES/ESA/EUMETSAT 2015
5. A. Cabarbaye, "Online reliability estimate of an orbiting satellite", CNES 2015
6. C. Dudal, "CNES miniaturization policy: an answer to Nanosatellites challenges", CNES 2019
7. "Space Systems - Space Debris Mitigation Requirements", ISO 24113:2011(E), 2011
8. "Space Debris Mitigation Policy for Agency Projects", ESA/ADMIN/IPOL 2, 2014
9. Law n° 2008-518 of the 3 June 2008 relative to space operations, consolidated version